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Value Assessment of Distribution Network Reconfiguration: A Danish Case Study

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Abstract

Distribution network reconfiguration is a mechanism that can improve the distribution system performance from multiple perspectives. In the context of smart grid wherein the degrees of automation and intelligence are high, the potential value of network reconfiguration can be significant. This paper presents a case study-based analysis to explore the potential value of reconfiguration in detail. The study is performed using a 10kV distribution grid of Denmark, while reconfiguration is applied to minimize the energy losses under both normal and post-fault conditions. The results show that although the reconfiguration is performed to achieve a single objective, the overall network performance is improved. In addition, the value achieved by reconfiguration can be very sensitive to the reconfiguration frequency and the associated cost.

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Keywords: Distribution network reconfiguration; Loss minimization; Network performance; Cost-benefit analysis.

1. Introduction

Network reconfiguration in a power distribution system is realized by changing the status of sectionalizing switches that are either normally closed or normally open. By changing the open/close status of the switches under different circumstances, many benefits can be potentially achieved, such as outage reduction, losses minimization, voltage control, congestion management, and component loading control, etc [1,2,3]. When discussing the circumstances of network reconfiguration, one must consider two very different operating conditions under which reconfiguration can occur – normal operation and fault situations. The variation of circumstances to a large degree determines the level of practicability of network reconfiguration. As an example, current practice of reconfiguration is mostly found in post-fault situations and is used for power restoration. In terms of normal operation, how to achieve loss minimization through computationally-efficient optimal network reconfiguration strategies from an operational planning perspective is also a massively investigated subject. In both circumstances, multi-purpose reconfiguration is also possible [4].

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Nomenclature

BCR	Benefit Cost Ratio
NE	Normal Event
LL	Line Loading
PF	Post Fault event
SAIDI	System Average Interruption Duration Index

Another important aspect that must not be overlooked when discussing network reconfiguration is the level of automation which in general can be categorized as manual, remote control, local automation, distributed automation and centralized automation [5]. Today, manual network reconfiguration is widely applied especially in MV and LV distribution systems. This is the most basic form of switching, slow and only useful for static changes performed by a technician. Remote control is still a process that needs to be activated by a person who places the command in the control center. This significantly reduces the time necessary to perform network reconfiguration. Compared to the above mentioned types of reconfiguration, location automation is the simplest automation process, allowing a secondary substation to change the state of switches based on locally measured information. The absence of human interaction allows it to act very fast; however, the use of local information limits the usefulness of this form of automation to that of outage reduction only. When distributed automation is referred to, it implies neighboring secondary substations can communicate with each other, therefore enabling each secondary substation has better knowledge of its role in the distribution system and can make more intelligent decisions on how to reconfigure the network. Based the coordinated actions, this form of automation has a high reliability and redundancy, because the failure of one secondary substation does not prevent the other secondary substations from coordinating their actions. The term centralized automation refers to all secondary substations communicate with control center where the optimal decision is carried out. The main advantage of centralized automation is that the complete picture of the distribution system could ensure a global optimal solution; however this requires a high level of redundancy for the central control system. Typically, remote control is considered as a backup of the centralized automation solution.

The third important factor that heavily affects the performance and the applicability of network reconfiguration is the effectiveness of decision support. In general, the level of global optimality in terms of distribution network performance achieved by various network reconfiguration solutions is highly dependent on the integrated performance of decision making and level of automation, as seen in Fig. 1. In other words, a manual solution derived from a good decision support may perform better than a centrally automated solution that is achieved based on a bad decision support, although speed-wise the manual solution is much slower.

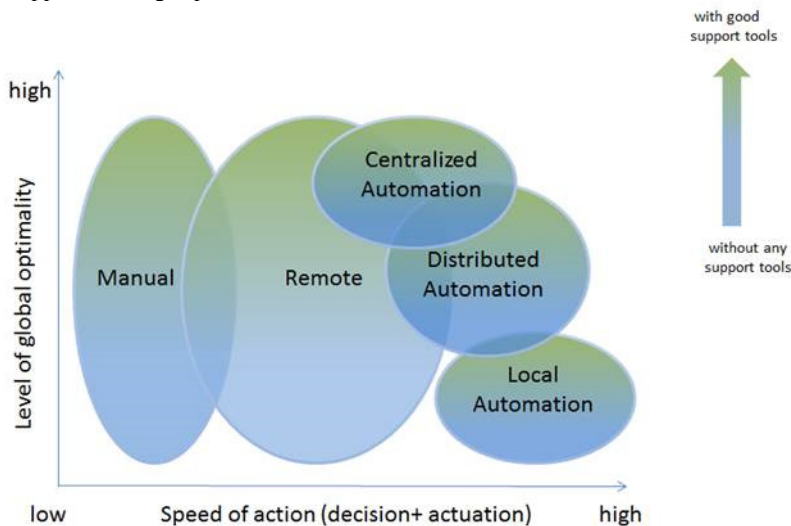


Fig. 1. A qualitative comparison of different automation solutions of distribution network reconfiguration.

In the context of a smart grid wherein both the levels of automation and decision support are high, there will be undoubtedly increased use of network reconfiguration [6]. Currently, one of the challenges with network reconfiguration today is the limited number of switching actions that switches and breakers for secondary

substations are capable of. This can significantly impact on the technical-economic performance of network reconfiguration. In the future this is likely to change, especially if distribution system operators (DSOs) start using network reconfiguration more actively. Technologies like solid state switches could radically change the costs associated with network reconfiguration and thus increase the attractiveness of using network reconfiguration. In order to better understand the potential benefits and the limits of network reconfiguration in a future smart grid, this study presents the results of an analysis based on a Danish case study.

2. Methodology

2.1. The distribution grid

The grid investigated in this study is a part of the 10kV grid in the northern area of Zealand, Denmark. It is a mixture of suburban and rural distribution system which is developed and operated as radial. As illustrated in Fig. 2, the 10kV grid is supplied by three 50/10kV primary substations ①-③, with 28 normally-open switches (highlighted in green) during normal conditions. Within the studied area, 461 loading points are supplied with electricity via 7 feeders, 382 10kV cables and 315 two-winding transformers. Each cable offers the possibility of being switched on/off at both ends. The grid is modelled in NEPLAN [7] which is also the tool used for the simulation-based analysis. Fig. 3 presents an overview of the load profile for the selected area based on the energy consumption data collected in 2013. The peak load is found on 29/12/2013 at 18:00 with 44.48MW; while the values of load factor (i.e. the average load divided by the peak load in one day) in spring and summer are relatively higher than the rest of the year, implying the load fluctuates much less in spring and summer than in the other seasons. With respect to the energy losses along the network (including all network elements), the ratio between the energy loss and the amount of energy consumption lies between 2.9% and 3.4% over the year 2013. Further, it is assumed the distribution system is centrally automated, implying a new network topology can be immediately achieved once the decision support function deployed at the control center found an optimal solution.



Fig. 2. Under-investigated 10 kV grid supplied by three primary substations with 28 normally-open switches

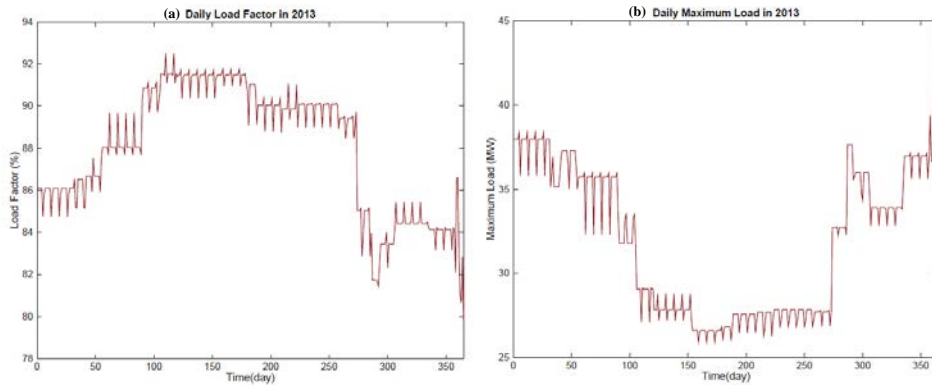


Fig. 3. An overview of the load profile (a) Daily load factor; (b) Daily maximum load.

2.2. Algorithm for achieving optimal reconfiguration

The commercially built-in algorithm for finding the optimal reconfiguration solution was known since 1980s [8] and has been improved over the years [9,10]. As concerns the theory part for this built-in algorithm, the goal of this procedure is to eliminate all network meshes by changing the network topology. Usually, there are a considerable number of possible topology states. The procedure chooses one topology that meets the objective (e.g. minimizes network losses), considering all active constraints and without creating isolated sub-systems. The procedure starts by considering all switchable elements in the selected voltage level are switched on, and then runs the following interactive processes:

1. Load flow calculation
2. Determination of the element with the lowest apparent power from all the switchable elements and elements that are not yet “worked off”.
3. Switch off the found element.
4. If the remained system contains an isolated part or if any constraint is violated, the element is switched on and is labelled as “worked off”.

The iteration continues until there is no switchable element or element that is not yet “worked off” left, resulting in a topology with the optimal separation points. Comparing to many advanced optimization algorithms such as genetic algorithms and robust optimization, etc., this algorithm shows a trade-off between optimality and efficiency. The time-efficiency for solving large-scale reconfiguration problems is quite high although the solution found might be local optimal rather than global optimal.

2.3. Cost of reconfiguration and energy saved

Reconfiguration is typically considered as a relatively expensive technology. According to [11], each switching action can cost 1.3\$ (i.e., 7.53DKK) and this figure is applied to the following analysis. The assumptions behind this estimation include 1) each automated switch costs 10000\$; 2) each remote actuator costs 3000\$ and 3) the average lifetime of switch and actuators is 10000 times.

The energy saved by reconfiguration also has a cost. In countries like Denmark where the power system is deregulated, the price of electricity varies from hour to hour. In this study, the average hourly electricity price 295.33DKK/MWh is used to estimate the cost of energy saved by doing reconfiguration. The electricity spot price in 2013 can be found [12], wherein the Danish transmission system operator records and publishes the wholesale market data.

3. Case studies

3.1. Single reconfiguration event for power loss reduction

To assess the value of reconfiguration in terms of power loss reduction, a loss minimization oriented optimal reconfiguration strategy is applied to seven different events, namely NE1-NE4 and PF1-PF3. The first four events

correspond to the four seasonal peak load instants respectively, and the others correspond to three randomly selected cable-outage events after which the reconfiguration is conducted to find the optimal network topology. The results are summarized in Table 1, wherein the number of switching actions is also presented.

Table 1. Summary of network performance improved by single reconfiguration event

Event	Time (Date, hour)	Load (MW)	Loss (%)		LL_max (%)		V_max (% 10kV)		V_min (% 10kV)		No. of switching
			before	After	before	After	before	After	before	After	
NE-1	02/03/2013, 19:00	35.95	3.36	3.03	73.92	72.01	104	104	96.85	98.34	42
NE-2	01/06/2013, 19:00	28.77	2.74	2.35	64.97	62.21	104	104	97.75	99.7	52
NE-3	14/10/2013, 18:00	37.65	3.27	2.95	74.07	73.04	104	104	96.37	98.11	42
NE-4	29/12/2013, 18:00	44.48	3.37	3.01	75.81	73.84	104	104	96.18	98.02	50
PF-1	29/12/2013, 18:00	44.48	4.61	4.00	73.84	72.25	104	104	96.21	98.51	42
PF-2	29/12/2013, 18:00	44.48	3.78	3.44	76.95	76.33	104	104	95.43	98.72	34
PF-3	29/12/2013, 18:00	44.48	4.97	4.43	75.81	75.81	104	104	97.72	99.13	38

It can be easily observed that for both normal and post-fault conditions, the loss-minimization oriented network reconfiguration operations are very effective. Taking NE-1 as an example, although the loss before reconfiguration is already very low, an optimal reconfiguration solution can further reduce the power loss by approximately 15%. Further, the minimum voltage V_min and the maximum cable loading LL_max recorded for each event also get raised and reduced respectively. This implies the network performance can be improved by reconfiguration in general, even though the objective is single and targets on loss minimization solely.

3.2. Multiple reconfiguration events for energy saving

An optimally reconfigured network solution is normally only effective for the moment-being it was derived for. At all other times, it may perform better or worse than the original network topology due to the change of operational condition. In order to ensure the effectiveness of reconfiguration, one of the approaches is to increase the frequency of reconfiguration. In Table 2, the cost-benefit analysis for reconfiguration strategies with different frequency is presented. As a result, the energy saved by reconfiguration is almost proportional to the increase of switching actions. When reconfiguration is carried out on hourly basis, the energy saved over 24 hours is up to 11.67% of the energy loss before reconfiguration. However, when the economic factors are taken into account, the benefit cost ratio (i.e. benefits over costs) is below 10% for all strategies. This implies using reconfiguration for loss reduction solely would not create a beneficial business cases for the DSO.

Table 2. Cost-benefit analysis for reconfiguration strategies with different frequency

Frequency of reconfiguration	Time (Date)	Energy saved (MWh)	No. of switching	Energy cost saved (DKK)	Reconfiguration cost (DKK)	BCR (%)
hourly	29/12/2013	2.98	1216	880.08	9156.48	9.61
every 3 hour	29/12/2013	0.98	403	289.42	3034.59	9.54
every 6 hour	29/12/2013	0.49	200	144.71	1506	9.61
every 12 hour	29/12/2013	0.23	100	67.93	753	9.02

4. Discussion and conclusion

As a mechanism that can be directly used by the DSO without involving any demand-side participation, network reconfiguration has the potential of being used to improve both temporary and long-term network performance under different conditions. In the Danish context, even though the current networks are very efficiently dimensioned and operated by the DSO, the potential value of network reconfiguration is still noticeable. For instance, as observed from the simulated results with data input from 2013, if an optimal recognition plan can be derived and deployed frequently, such as on hourly basis, the energy loss of the current system can be further reduced more than 10%.

However, to fully achieve such value requires enormous development and investment on distribution automation and optimal decision support tools. Because reconfiguration is primarily used for outage reduction in the current practice; neither distribution automation nor optimal decision support tools are commercially ready to support frequent use of optimal reconfiguration in grid operation. Further, the life span of switchgear

could be another limiting factor prohibiting frequent reconfigurations, although this might be improved if solid state switches are massively deployed.

The current effort made by the Danish DSOs on improving the observability of distribution networks by having more intelligent substations and measurement devices would to a great extent support the application of network reconfiguration. Although at the present stage, it is still difficult to derive and apply reconfiguration for optimized grid operation at a system level based on these efforts, it is expected that the improved observability could better support reconfiguration applications in outage reduction and the reliability such as SAIDI etc. One of the recent research [13] conducted by the same author group has demonstrated the economic viability of smart substations for improving the distribution grid reality and the cost of outage.

Regarding other future analysis, it is recommended to further investigate the potential value of network reconfiguration. For instance, the studied Danish distribution grid has sufficient capacity of power distribution, implying there are few issues with loading and voltage. In the future, when there is a high share of DER, it is highly possible for the distribution grid to have more grid issues if reinforcement/other mechanisms are not implemented timely. Therefore, from both grid operation and grid planning perspectives, it is important to evaluate the technical-economic feasibility of using reconfiguration as an alternative/part of an integrated mechanism (such as a combined use of network reconfiguration and demand-side flexibility) for improvement of network performance on a regular basis.

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